The high mass end of extragalactic globular clusters

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Abstract

In the last decade, a new kind of stellar systems has been established that shows properties in between those of globular clusters (GCs) and early-type dwarf galaxies. These so-called ultra-compact dwarf galaxies (UCDs) have masses in the range 10^6 to 10^8 $M_\odot$ and half-light radii of 10-100 pc. The most massive UCDs known to date are predominantly metal-rich and reside in the cores of nearby galaxy clusters. The question arises whether UCDs are just the most massive globular clusters in rich globular cluster systems? Although UCDs and 'normal' GCs form a continuous sequence in several parameter spaces, there seems to be a break in the scaling laws for stellar systems with masses above $\sim 2.5 \times 10^6$ $M_\odot$. Unlike GCs, UCDs follow a mass-size relation and their mass-to-light ratios are about twice as large as those of GCs with comparable metallicities. In this contribution, I present the properties of the brightest globular clusters and ultra-compact dwarf galaxies and discuss whether the observed findings are compatible with a 'star-cluster' origin of UCDs or whether they are more likely related to dark matter dominated dwarf galaxies.

1 The most massive globular clusters of a galaxy

ω Centauri is the most luminous and massive globular cluster of our Galaxy. With an absolute magnitude of $M_V = -10.29$ mag (Harris 1996) and a mass of $2.5 \times 10^6 M_\odot$ (van de Ven et al. 2006), it is an order of magnitude more luminous and massive than an average Galactic globular cluster ($M_V = -7.5$, $2 \times 10^5 M_\odot$). But can ω Cen actually be regarded as a globular cluster? Several studies over the past decade have shown that ω Cen is composed of multiple stellar populations with different, rather discrete abundance patterns and probably a spread in their ages (e.g. Hilker & Richtler 2000, Bedin et al. 2004, Sollima et al. 2005, Villanova et al. 2007). Such a complex behaviour is usually only seen in galaxies, like the Local Group dwarf spheroidals (for example the Carina dSph: Koch et al. 2007).

The view of globular clusters (GCs) as simple stellar systems was even more revolutionised by studies based on precise HST-based photometry that revealed multiple stellar populations in several massive Galactic globular clusters (e.g. Piotto et al. 2007, Milone et al. 2008). But this is the story of

another review in this book (see the contribution by Piotto). Here I concentrate on the properties of the most massive globular clusters in external galaxies, and even more massive compact stellar systems in galaxy clusters.

Departing from the Milky Way we can first ask what are the properties of the most massive globular clusters in other Local Group galaxies?

The Andromeda galaxy has a $\sim$3 times larger globular cluster system (GCS) than our Galaxy (e.g. Barmby et al. 2001) and possesses several GCs that are $\sim$3 times more luminous/massive than ω Cen. In particular G1, one of the most massive clusters in M31, exhibits a spread in its red giant branch, probably caused by multiple stellar populations of different metallicities (Meylan et al. 2001). At the lower mass end of Local Group galaxies, old GCs (> 5 Gyr) are known in the LMC and SMC (LMC: Mackey & Gilmore 2004; SMC: Crowl et al. 2001, Glatt et al. 2008), the dwarf ellipticals NGC 205, NGC 185 and NGC 147 (Hodge 1993, 1974, 1976; Da Costa & Mould 1988), and the Fornax and Sagittarius dwarf (Sgr) spheroidals (For dSph: Buonanno et al. 1999, Mackey & Gilmore 2003; Sgr dSph: Carraro et al. 2007; Carraro 2009). The most luminous GCs in these galaxies are 2-3 magnitudes fainter than those in the Milky Way and Andromeda (see Table 1 and Fig. 2).

Going to denser environments and more massive galaxies beyond the Local Group we can then ask whether the trend of more luminous/massive GCs in ever more luminous galaxies continues or whether there exists some kind of cut-off mass for the most massive GC? How massive can a GC get?

Finding the most massive GC in distant galaxies is not an easy task. Since distant GCs are not resolved on ground based images, contamination by foreground stars and compact background galaxies hampers the exact definition of the sparsely sampled bright end of the globular cluster luminosity function (GCLF). Only massive spectroscopic surveys and the resolved appearance of GCs on HST images made it possible to discover the brightest GCs at distances beyond the Local Group. In this respect, the best studied GCSs of nearby elliptical galaxies are those of Centaurus A (e.g. Peng et al. 2004, Rejkuba et al. 2007), NGC 1399 (Drinkwater et al. 2000, Mieske et al. 2004) and M 87 (Haşegan et al. 2005, Jones et al. 2006), the central galaxies of the Centaurus group, the Fornax and the Virgo cluster, respectively. Indeed, compact sources with masses up to a hundred times that of ω Cen have been identified. Their discovery history and properties are described in the next section.

2 Ultra-Compact Dwarf Galaxies

The discovery history of very massive compact objects started about 10 years ago. In a small spectroscopic survey of the globular cluster system of NGC 1399, Minniti et al. (1998) confirmed a bright compact object as radial velocity member of the cluster: *'... Note that the object at $V = 18.5$, $V - I = 1.48$ (our reddest "globular cluster"), which has $M_V = -12.5$, was identified as a compact dwarf galaxy on the images after light-profile analysis (M. Hilker,*

Table 1: Properties of brightest GCs and UCDs and their host galaxies.

Galaxy	$M_{V,\mathrm{gal}}$ [mag]	$N_{\mathrm{GC,tot}}$	σ_{GCLF} [mag]	GC Name	$M_{V,\mathrm{GC}}$ [mag]	log(M) $\mathrm{M}_{\odot}$
Fnx dSph	−13.1	5	0.50	Fnx3	−7.80	5.560
				Fnx2	−7.05	5.260
Sgr dSph	−15.0	7	0.60	M54	−8.55	5.857
				Arp 2	−5.60	4.040
NGC 147	−15.1	4	0.60	NGC 147-3	−7.93	5.484
				NGC 147-1	−7.23	5.222
NGC 185	−15.6	8	0.65	NGC 185-5	−7.83	5.479
				NGC 185-3	−7.73	5.447
NGC 205	−16.4	8	0.70	NGC 205-8	−8.19	5.606
				NGC 205-2	−8.09	5.599
SMC	−17.1	8	0.80	Kron 3	−8.00	5.350
				NGC 121	−7.94	5.550
				NGC 416	−7.70	5.270
LMC	−18.5	16	0.90	NGC 1898	−8.60	5.880
				NGC 1835	−8.33	5.830
				NGC 1916	−8.33	5.790
Milky Way	−20.9	150	1.15	ω Cen	−10.29	6.398
				NGC 6715	−10.01	6.240
				NGC 6441	−9.64	6.170
M31	−21.2	460	1.20	B023	−11.33	6.955
				G1	−10.94	6.863
				B225	−10.75	6.778
Cen A	−21.5	1550	1.30	HCH99-18	−11.38	7.050
				HGHH92-C1	−10.84	6.833
				HGHH92-C23	−11.66	6.822
NGC 1399	−21.9	6450	1.25	UCD3	−13.40	7.971
				UCD1	−12.07	7.507
				UCD6	−12.50	7.476
M87	−22.4	14660	1.30	VUCD7	−13.42	7.946
				VUCD3	−12.59	7.602
				VUCD5	−12.32	7.464

1996, private communication) ...” (see also Hilker 1998). In another spectroscopic survey on dwarf ellipticals in the Fornax cluster, Hilker et al. (1999) confirmed two bright compact objects with $M_V = -13.4$ and -12.6 mag (including the one mentioned before) as Fornax members. They proposed that they *‘... can be explained by a very bright GC as well as by a compact ellip-*

tical like M32. Another explanation might be that these objects represent the nuclei of dissolved dE,Ns ...'. Furthermore they suggested that *'... It would be interesting to investigate, whether there are more objects of this kind hidden among the high surface brightness objects in the central Fornax cluster ...'*.

Indeed, only one year later, in 2000, a systematic all-object spectroscopic survey within in a 2-degree field centred on the Fornax cluster revealed five compact Fornax members in the magnitude range $-13.5 < M_V < -12.0$ (Drinkwater et al. 2000) which later, in 2001, were dubbed "Ultracompact Dwarf Galaxies" (UCDs) by Phillipps et al. (2001). Their physical properties were presented in a *Nature* article by Drinkwater et al. (2003). Later, Mieske et al. (2004) identified compact objects in the brightness range $-12.0 < M_V < -10.0$ mag. They found that their luminosity distribution is consistent with an extrapolation of the Gaussian-shaped GC luminosity function.

After the first discovery of UCDs in the Fornax cluster, many surveys followed to search for UCDs in different environments and towards fainter magnitudes (Virgo cluster (M87): Haşegan et al. 2005, Jones at al. 2006; Centaurus cluster (NGC 4696): Mieske et al. 2007; Hydra I cluster (NGC 3311): Misgeld et al. 2008; Cen A: Rejkuba et al. 2007; Sombrero: Hau et al. 2009). Although massive UCDs mainly are found in galaxy clusters and therefore might be linked to the overall cluster formation process, most of them seem to be associated to giant galaxies. Regarding their radial distribution and kinematic signature around their host galaxies, UCDs can hardly be distinguished from luminous/massive genuine globular clusters belonging to those galaxies. Therefore, I consider objects more luminous than $M_V < -11$ mag – GCs as well as UCDs – as one class and simply call them 'UCDs' or sometimes 'GCs/UCDs' throughout this contribution, being aware of the fact that the formation processes of UCDs in the cluster environment and massive GCs around individual galaxies might be different.

Once the existence of UCDs was proven by radial velocity measurements, further studies focused on their physical parameters. In particular, their sizes, metallicities, ages, internal kinematics, masses and mass-to-light ratios were investigated. The most important results are summarized in the following.

UCDs are luminous ($-11.0 < M_V < -13.5$), have half-light radii in the range $10 < r_\mathrm{h} < 100$ pc and are predominantly old (> 10 Gyr) (e.g. Mieske et al. 2006; Evstigneeva et al. 2007). As opposed to GCs, UCDs follow a luminosity-size relation (e.g. Haşegan et al. 2005; Evstigneeva et al. 2008). M32-type galaxies lie on the extension of this relation (Dabringhausen et al. 2008). Also nuclei of early-type galaxies exhibit a luminosity-size relation, shifted towards smaller sizes at a given luminosity (Côté et al. 2006). The two brightest UCDs in Fornax (UCD3) and Virgo (VUCD7), both with $M_V \simeq -13.5$, are at least twice as luminous as the second brightest UCD in their respective clusters. They exhibit faint surface brightness envelopes with effective radii of $80 < R_\mathrm{eff} < 120$ pc (Evstigneeva et al. 2007).

In the colour-magnitude diagram (see Fig. 1), UCDs cover the full colour range of 'normal' GCs. However, the brightest UCDs are found on the extension of the red (metal-rich) GC population (Mieske et al. 2006; Wehner &

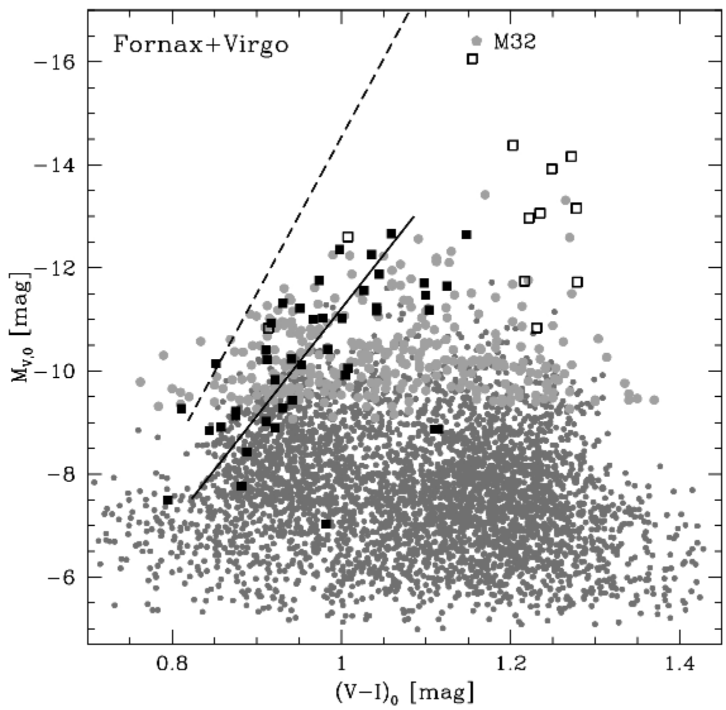

Figure 1: Colour magnitude diagram of GCs, UCDs and nuclear clusters in the Fornax and Virgo clusters. Small grey dots represent GCs around NGC 1399 and NGC 1404 (Jordán et al. 2009) and M 87 and M 49 (Peng et al. 2006) from HST/ACS data. Large grey dots are confirmed cluster members (Hilker 2009, in prep.) and filled and open squares mark the nuclei of early-ype galaxies in Virgo (Côté et al. 2006). The solid line is a fit to the filled squares, whereas the dashed line represents the colour-magnitude relation of dEs in Fornax (Mieske et al. 2007b). The location of M32 is shown as well.

Harris 2008). Blue (metal-poor) UCDs coincide with the location of nuclear clusters in early-type dwarf galaxies.

The central velocity dispersions of UCDs range from 15 to 45 km s^{-1}, resulting in dynamical masses of $2 \times 10^6 < M < 10^8 M_\odot$ (e.g. Hilker et al. 2007, Mieske et al. 2008). The most remarkable consequence of these derived masses is that the dynamical mass-to-light ratio of UCDs is on average twice that of GCs at comparable metallicity and cannot be explained by stellar population models with a canonical initial mass function (IMF, e.g. Kroupa 2001) (Haşegan et al. 2005, Dabringhausen et al. 2008, Mieske et al. 2008). The large M/L values of UCDs might either be caused by an unusual IMF (bottom-heavy: Mieske & Kroupa 2008; top-heavy: Dabringhausen et al. 2009) or by the presence of dark matter (Baumgardt & Mieske 2008).

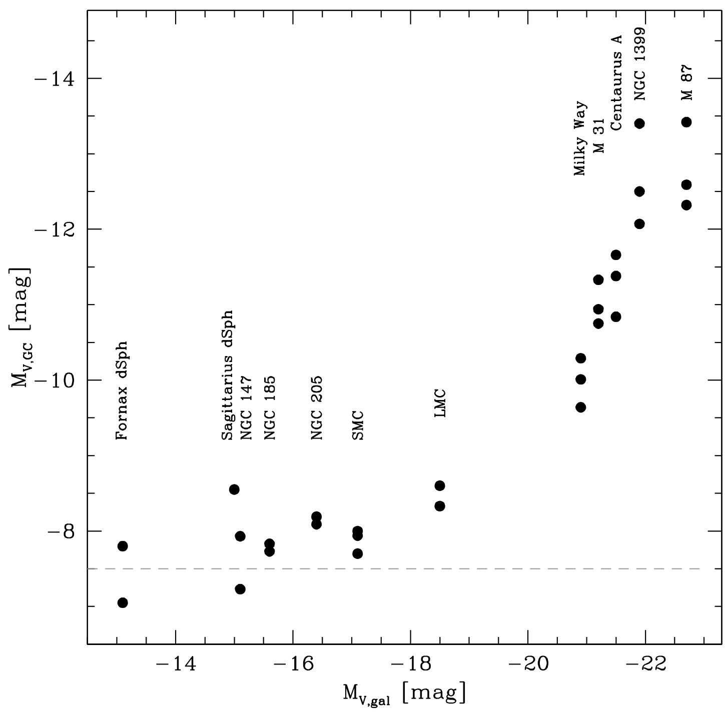

Figure 2: The absolute magnitude of the brightest two or three GCs/UCDs of a galaxy as a function of host galaxy luminosity. The dashed line indicates the universal luminosity of the GCLF turnover magnitude.

All the properties presented above and the scaling relations of UCDs hint to a characteristic transition mass of $M_c \simeq 2.5 \times 10^6 M_\odot$ between GCs and UCDs. This does not necessarily mean that GCs and UCDs are different kinds of objects. It might just reflect a change in the physics of cluster formation at this characteristic mass, for example, if more massive clusters become optically thick to far infrared radiation when they formed and are born with top-heavy IMFs (Murray 2009).

In the next section we will investigate whether the transition from GCs to UCDs can be seen in the luminosity and mass function of well studied globular cluster systems and UCD populations.

3 Luminosity and mass function of GCs/UCDs

In Fig. 2 the luminosities of the two or three brightest GCs (and UCDs) are plotted as function of host galaxy luminosity for all the galaxies discussed in Sect. 1 (see the parameters of the GCs and galaxies in Table 1, taken from

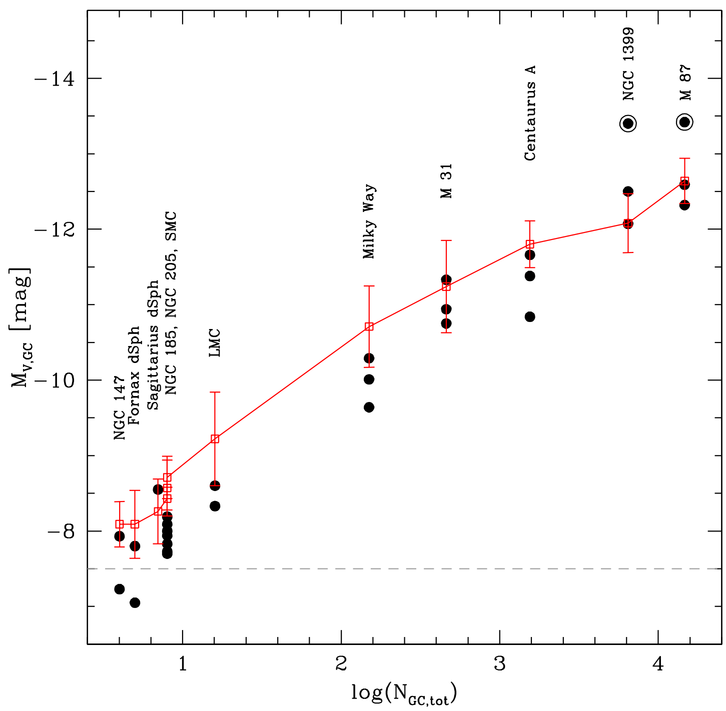

Figure 3: The absolute magnitude of the brightest two or three GCs/UCDs of a galaxy as a function of total number of GCs belonging to the host galaxy. The open squares with errobars indicate the average luminosity of the brightest GC from Monte Carlo simulations of 10.000 GCLFs of the respective galaxies. The two brightest UCDs in Fornax and Virgo (encircled dots) have extended low surface brightness envelopes. The dashed line marks the universal luminosity of the GCLF turnover magnitude.

NED, van den Bergh 2000, Harris 1996, McLaughlin & van der Marel 2005, and other works for the UCDs as given in the text). Clearly, more luminous galaxies possess more luminous GCs/UCDs. Is this just a sampling effect reflecting the ever richer globular cluster systems?

Many studies of the globular cluster luminosity function (GCLF, number of GCs vs. magnitude) have shown that the bright end shape can be well described by a Gaussian with a universal turnover magnitude at $M_V = -7.5$ mag (see Richtler 2003 and references therein). The dispersion of the GCLF, $\sigma_{\rm GCLF}$, ranges from 0.8 to 1.3 mag and increases with increasing host galaxy luminosity (Jordán et al. 2007). To test the hypothesis that the brightest GCs are statistically compatible with a Gaussian GCLF, we determined the average luminosity of the brightest GC from Monte Carlo simulations of 10.000 GCLFs of our sample galaxies. The GCLF function is defined by the total

number of GCs, $N_{\mathrm{GC,tot}}$ and its width σ_{GCLF} (see Table 1). In Fig. 3 the results of those simulations (open squares with errorbars) are shown together with the brightest GCs. With the exception of the brightest UCD in the Fornax and Virgo cluster (encircled dots), the brightest GCs/UCDs of all galaxies are compatible with being drawn from a Gaussian GCLF. This is at odds with what one would expect if UCDs were a distinct kind of objects (as discussed in the previous section). Also there is no hint for a maximum luminosity of a GC/UCD. The absolute magnitudes of the brightest GCs linearly increase with the logarithm of $N_{\mathrm{GC,tot}}$ (see also Billett et al. 2002, Weidner et al. 2004). At first glance, these findings might pose a problem for the hierarchical assembly of the most massive galaxies. If a central cluster galaxy like NGC 1399 is the result of a merger of several L^* or Milky Way-type galaxies, one would expect the brightest GCs of the resulting merger to have a luminosity of about ω Cen. On the other hand, just during those mergers the most massive GCs/UCDs might have formed. I come back to this point in the next section.

Before that, let us have a look at the mass function of GCs and UCDs in the central Fornax cluster. The GCS of NGC 1399 has the most complete coverage of confirmed radial velocity members at the bright end of the GCLF, thanks to massive spectroscopic surveys (Drinkwater et al. 2000, Richtler et al. 2004, Mieske et al. 2004, Firth et al. 2007). More than 150 GCs/UCDs brighter than ω Cen are known (Hilker 2009, in prep.). The bulk of the lower mass GCs is well defined through the Fornax ACS survey (Jordán et al. 2009). Both datasets combined have been used to construct the mass function of GCs and UCDs around NGC 1399. First, the gz photometry of the ACS data were transformed into the Johnson V,$(V-I)$ system using the relation of Peng et al. (2006, see also the CMD in Fig. 1). Second, the mass-to-light ratio, M/L_V, of each GC/UCD was derived from its $(V-I)$ colour, using a fit to the $(V-I)$ and M/L_V values of a 13-Gyr old single stellar population model by Maraston (2005). A Kroupa IMF and a blue horizontal branch was assumed (see also Dabringhausen et al. 2008). M/L_V and M_V, finally, were used to compute the masses of the GCs and UCDs.

In Fig. 4 the mass function of both samples is shown. The number counts of the ACS data were normalized to those of the spectroscopic sample in the mass range $6.5 < \log M < 6.8 M_\odot$, a regime where both datasets are expected to be complete. The turnover magnitude $M_V = -7.5$ mag corresponds to $\log M \simeq 5.4$ which forms a plateau in the mass function. For masses larger than $\log M > 5.8$ the number counts are decreasing, but not with a uniform slope. In the mass range $5.5 < \log M < 6.4$ a fit to the data gives a power-law slope of $\alpha = -1.88$ (from $dN/dM \propto M^{-\alpha}$) which also was found for other GCSs (e.g. Harris & Pudritz 1994, Larsen et al. 2001) and which is close to $\alpha = -2$, the typical slope for the mass functions of young cluster in merger galaxies (e.g. Zhang & Fall 1999) and giant molecular clouds (e.g. Elmegreen 2002 and references therein). Beyond $\log M > 6.5$ the mass function falls off steeply. A fit to the data gives a slope of $\alpha = -2.70$. Interestingly, both fits cross at $\log M \simeq 6.4$, just the characteristic mass where the properties

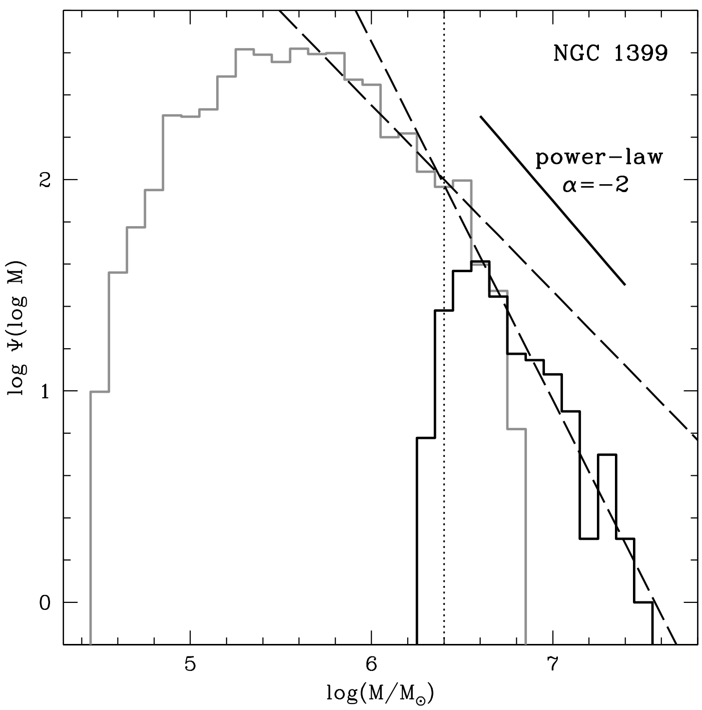

Figure 4: Mass function of GCs and UCDs around NGC 1399. The GCs (grey histogram) were taken from the Fornax ACS survey (Jordán et al. 2009). The black histogram is based on radial velocity members of the Fornax cluster (GCs and UCDs, Hilker 2009, in prep.). The grey histogram was normalized to the number counts of the black histogram at $\log M \simeq 6.6 M_\odot$. The dashed lines are fits to the mass regimes $5.5 < \log M < 6.4$ and $6.6 < \log M < 7.5$ with power-law slopes α of -1.9 and -2.7, respectively. The dotted vertical line indicates the characteristic transition mass of $M_c = 2.5 \times 10^6 M_\odot$ between GCs and UCDs.

and scaling relations between GCs and UCDs change ($M_c = 2.5 \times 10^6 M_\odot$). Maybe there is some kind of cut-off mass for 'normal' GCs, and UCDs indeed follow a different formation mechanism?! Such a cut-off at the high mass end of the mass function was also observed for young star clusters systems in spirals (e.g. Gieles et al. 2006), although at an order of magnitude lower mass (Schechter function cut-off mass: $M_c = 2.1 \times 10^5 M_\odot$, Larsen 2009). For early-type galaxies in the Virgo cluster, Jordán et al. (2007) describe the GC mass function by an "evolved Schechter function" and show that M_c increases from $3 \times 10^5 M_\odot$ in bright dwarf ellipticals ($M_V = -16$) to 2-3$\times 10^5 M_\odot$ in giant ellipticals, consistent with what is presented here.

Fig. 5 illustrates that the high mass end of GCs/UCDs is dominated by

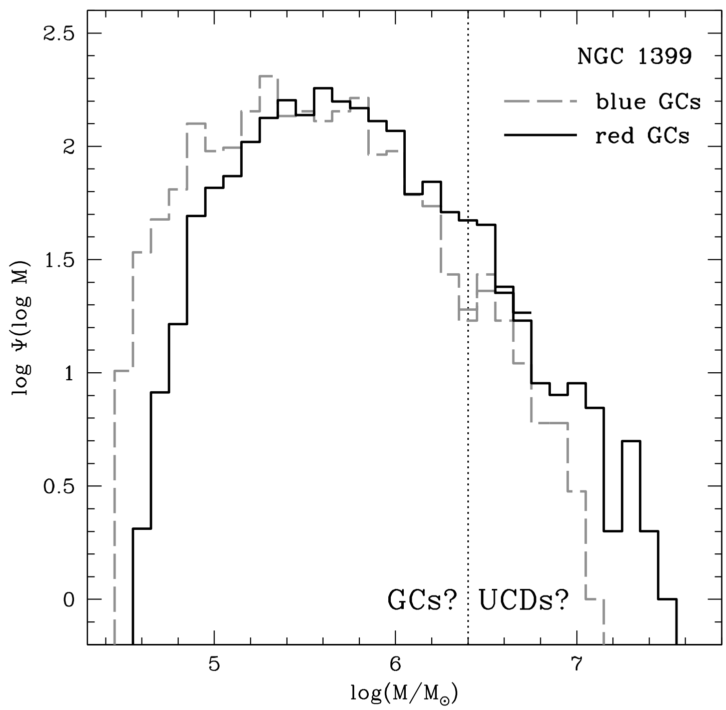

Figure 5: Mass function of GCs and UCDs around NGC 1399 (see Fig. 4), separated into blue (metal-poor) and red (metal-rich) GCs/UCDs as indicated. The histograms of the GCs were normalized to the number counts of the confirmed Fornax members at $\log M \simeq 6.5 M_\odot$ and $\log M \simeq 6.7 M_\odot$ for the blue and red GCs, respectively. The dotted vertical line indicates the characteristic transition mass of $M = 2.5 \times 10^6 M_\odot$ between GCs and UCDs.

metal-rich objects. As a division between blue (metal-poor) and red (metal-rich) GCs/UCDs a colour of $(V - I) = 1.05$ mag ([Fe/H]$\simeq -0.8$ dex) was chosen (see Fig. 1). This colour corresponds to the well known dip in the bimodal colour distribution of GCs in elliptical galaxies (e.g. Gebhardt & Kissler-Patig 1999).

4 Formation scenarios for UCDs

Various formation scenarios have been suggested to explain the origin of UCDs. The three most promising and their implications concerning the presented properties of UCDs are:

1) UCDs are the remnant nuclei of galaxies that have been significantly stripped in the cluster environment (e.g. Bassino et al. 1994, Bekki et al.

2001). Numerical simulations have shown that nucleated dEs can be disrupted in a galaxy cluster potential under specific conditions and that the remnant nuclei resemble UCDs in their structural parameters (Bekki et al. 2003) and mass-to-light ratio (Goerdt et al. 2008). In Fornax and Virgo, the small number of UCDs in both clusters points to a rather selective "threshing" process. The high metallicity of most Fornax UCDs seems to disfavour this scenario for their origin, whereas the brightest, metal-poor GCs/UCDs indeed share most of the properties of present-day nuclei. Note that that the threshing process also seems to work in our Galaxy. Good candidates for (former) nuclei are ω Cen (e.g. Hilker & Richtler 2000) and M54, the nuclear cluster of the Sagittarius dSph (e.g. Monaco et al. 2005).

2) UCDs have formed from the agglomeration of many young, massive star clusters that were created during merger events (e.g. Kroupa 1998, Fellhauer & Kroupa 2002), like the Antennae galaxies where many young super-star cluster complexes were found (e.g. Whitmore et al. 1999). An evolved example of such a merged star cluster complex might be the 300 Myr old, super-star cluster W3 in NGC 7252 (Maraston et al. 2004, Fellhauer & Kroupa 2005). Indeed, a further passive evolution of W3 would bring it into the regime of the most massive, metal-rich UCDs. Moreover, the young massive star clusters in starburst/merger galaxies follow a mass-size relation that is consistent with that of UCDs (Kissler-Patig et al. 2006). If the old UCDs in Fornax and Virgo formed like this, the galaxy mergers must have happened early in the galaxy cluster formation history when the merging galaxies were still gas-rich. However, these early mergers must have already possessed close to solar metallicity gas or they were self-enriched fast. Moreover, the stellar mass function of the young star clusters must have been non-canonical to explain the elevated M/L values of UCDs. The small number of UCDs would imply that only the most massive star cluster complexes survived as bound systems (e.g. Bastian et al. 2006).

3) UCDs are the brightest globular clusters and were formed in the same GC formation event as their less massive counterparts (e.g. Mieske et al. 2004). The smooth shape of the bright end of the GC luminosity function (no excess objects!) might support this scenario. The most massive GCs then supposedly formed from the most massive molecular clouds (MCs) of their host galaxy, assuming that more massive galaxies (like M87) were able to form higher mass MCs than lower mass galaxies (like M31). The luminosity-size relation of the most massive clusters suggests that there is a break of the formation/collapse physics at a critical MC mass. The high M/L values of the most massive GCs then would point either to a formation of GCs in dark matter halos (e.g. Baumgardt & Mieske 2008 and references therein) or to a non-canonical (probably top-heavy) IMF that accompanies the formation of the most massive GCs (e.g. Murray 2009, Dabringhausen et al. 2009).

4) UCDs are genuine compact dwarf galaxies, maybe successors of ancient blue compact dwarf galaxies, that formed from small-scale peaks in the primordial dark matter power spectrum (Drinkwater et al. 2004). This scenario has

the advantage that no external processes, like mergers or tidal disruption, are needed. However, due to the small numbers of UCDs, this formation channel then seems to be a rare event and one might ask why no compact galaxies with a mass inbetween UCD3 (in Fornax) and M32 have been found.

Which of these scenarios tells us the truth? Why is there a characterstic mass at which the scaling relations and the slope of the mass function changes?

It is widely accepted that globular clusters are formed inside the cores of supergiant molecular clouds (e.g. McLaughlin & Pudritz 1996). The balance between coagulation and disruption processes of these cores shapes the GC mass spectrum. Up to a final cluster mass of $\sim 10^6 M_\odot$ this seems to be a well regulated scale-free process. Does the break in the GC mass function correspond to a maximum 'allowed' molecular cloud mass from which a GC can form? If so, all GCs/UCDs above the corresponding 'maximum' GC mass must have formed from the coalescence of lower mass GCs (or proto-GCs). This can have happend on a very short timescale during the GC formation process itself or on a longer timescale via the merging of individual GCs either in a compact star cluster complex (e.g. Fellhauer & Kroupa 2002) or through tidal friction in the core of a dwarf galaxy (e.g. Oh & Lin 2000). Also, a nucelar star cluster can grow via episodic star formation triggered by infalling gas in the centre of a gas-rich galaxy (e.g. Walcher et al. 2006). Alternatively, if there does not exist a maximum 'allowed' molecular cloud mass, the physics of the massive cluster formation within the MCs must be different than for lower mass GCs (see Murray 2009 for a possible solution).

It is not up to this contribution to discuss which scenario is the most plausible one. Since UCDs come with different flavours (metal-poor vs. metal-rich; with and without low surface brightness envelope; etc.) they probably comprise a 'mixed bag of objects' from different formation channels.

5 Conclusions and Outlook

The most massive globular cluster of a galaxy scales with the luminosity of the host galaxy and the richness of the globular cluster system. When taking a Gaussian function as representation of the bright end of the globular cluster luminosity function, no excess objects are needed to explain the most luminous GCs in their respective environments. This includes the so-called "ultra-compact dwarf galaxies" (UCDs) which were identified as the brightest compact ($R_{\rm eff} < 100$ pc) objects in nearby galaxy clusters, but also around individual galaxies. Although there seems to exist a smooth luminosity function between GCs and UCDs, the mass function shows a break at a characteristic mass of $M_c \simeq 2.5 \times 10^6 M_\odot$. Whereas GCs in the mass range $3.0 \times 10^5 < M < 2.5 \times 10^6 M_\odot$ follow a power-law slope of $\alpha \simeq -1.9$ consistent with the measured power spectrum of molecular clouds and young star clusters, compact objects (GCs/UCDS) above M_c are not as abundant as 'normal' GCs. The slope falls off with an exponent $\alpha \simeq -2.7$. Strikingly, this characteristic mass also marks the change of some key properties between

GCs and UCDs. The most remarkable properties of UCDs are that their size scales with their luminosity and that their dynamical mass-to-light ratio is on average twice that of GCs at a given metallicity. Moreover, the most massive UCDs seems to be exclusively metal-rich. Although many of these characteristics are consistent with the known scaling relations and properties of early-type galaxies, there exists a prominent gap bewteen the most massive UCDs and the M32-type galaxies, the latter being ~ 15 times more massive than UCDs. This makes it unlikely that UCDs are pure genuine compact galaxies related to small-scale dark matter clumps. Rather they are connected to gas-dynamical cluster formation processes, either as nuclear star cluster of nowadays dissolved galaxies or as merged super-star clusters which formed in violent starbursts such as seen in merging galaxies. The latter scenario is supported by the existence of young massive star clusters with similar masses and scaling relations as those of UCDs. The elevated M/L values of UCDs, however, suggests that they were born with a different (probably top-heavy) initital mass function than lower mass GCs.

While we have some ideas on the possible origin of UCDs, there are many questions left to answer concerning their nature. Some important ones are: Do UCDs have multiple stellar populations? Can we find young or intermediate age UCDs in the local universe? Do the large M/L values really point to unusual initial mass functions? Or do they contain dark matter? Is there tidal structure around UCDs? Do UCDs harbour black holes?

Some of these questions will be answered in the next years with the help of ongoing and future observing programmes. The results will bring more light into the nature of these enigmatic objects.

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